KIMBERLITE:

OCCURRENCE, GENESIS, AND EXPLORATION

Senior Thesis

by

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INTRODUCTION

Diamonds were discovered more than a century ago in alluvial gravels in streams around what is now the South African city of Kimberely. Tracing the detrital stones upstream to their source led to the discovery of strange volcanic vents known as kimberlite pipes. Since that time, considerable research has gone into describing these unique geologic features. Many volumes have been written describing the occurrence, petrology, and origin of kimberlites. Each new discovery has revealed secrets about the interior of the Earth, but much still remains to be learned about both the Earth's interior and about the kimberlites themselves. Specifically, it cannot be said for certain exactly how a kimberlite melt forms in the Earth, or if the ultramafic xenoliths brought to the surface by kimberlites are samples of the upper mantle or of the lower continental crust. Peridotite and eclogite xenoliths found in some kimberlites, as well as diamonds, indicate extremely high pressures and great depths of formation. This evidence suggests an upper mantle origin, while some isotopic evidence from the xenoliths suggests an origin from the lower continental crust.

This paper will discuss some of the more plausible interpretations of the various characteristics of kimberlites, and also give examples of the surface expressions of kimberlite features as currently understood.

KIMBERLITE - A DESCRIPTION

A non-genetic definition of kimberlite describes the rock as an inequigranular, ultramafic igneous rock, rich in volatile concentration (having high amounts of H_2O and CO_2 concentrated in the intrusive body), and containing olivine as the primary mineral, plus varying amounts of phlogopite, magnesian ilmenite, spinels, perovskite, clinopyroxene and carbonate minerals. Much of the olivine may be altered to serpentine, while late-stage carbonation can produce masses of calcite and/or dolomite. Serpentine also is present in late-stage masses, many times closely associated with the carbonate mineralization. The inequigranular texture of kimberlite is attributed to the formation of macrocrysts during melt generation in a primarily microporphyritic matrix (Clement et al., 1977). Large mantle xenoliths and monomineralic xenocrysts provide these macrocrysts. Pyrope-rich garnets and ilmenite grains form the larger fractions of the macrocrysts (Pasteris, 1981).

Elemental compositions of kimberlites have determined by several researchers. Kimberlites are undersatured rocks having a silica content of about 33 weight percent, and the alumina and titania contents are high in comparison to other ultramafic rocks. The iron content is about that expected for ultramafic rocks, being generally about 9 weight percent FeO (Pasteris, 1981). Kimberlites are highly alkalic rocks, and some have a Potassium : Sodium ratio of 3 or greater.

The volatile content in kimberlites (percent H_2O and CO_2) also is quite high, which may help to explain the explosive nature of intrusion of many of the known kimberlite pipes. Any sudden release of confining pressure would cause rapid devolatilization, releasing H_2O and CO_2, and simultaneously vessiculating and crystallizing the mass. A process such as this would give rock with a brecciated texture; and most kimberlites are indeed brecciated and jumbled in texture.

XENOLITHS

Ultramafic nodules of peridotite and eclogite, metamorphic and igneous rocks from basement groups, and crustal inclusions all have been found in kimberlite pipes. These inclusions can be of considerable size. According to Hawthorne et al. (1979), blocks of wallrock larger than one meter in diameter are present in the Dokolwayo kimberlite pipe in northeast Swaziland. Included ultramafic nodules often are rounded and polished from abrasion during the fluidlike ascent of the explosively intruding body. The abraded character of the ultramafic xenoliths suggests a solid-state transport from depths of up to 150 kilometers, because striations could not have been formed if these xenoliths had been transported in the liquid state. Abrasion by transport within a fluidized gas column is the means that accounts for both the abraded xenoliths and for the low degree of thermal alteration of many of these xenoliths.

The small amount of thermal alteration of included material in the highly brecciated upper components of kimberlite pipes suggests that the temperature of intrusion was quite low, compared to more magmatic intrusions. Coal present in the xenogenic material of the Dokolwayo pipe

(Hawthorne et al., 1979) further supports a low temperature of formation within brecciated portions of kimberlites. The blocks of coal show very little thermal alteration, and certainly would have been considerably altered, perhaps burned up completely, in a heated magmatic intrusion.

Fragments can make up as much as 90 percent of kimberlite pipes. The fragments consist of both kimberlitic and xenogenic material (Ehlers and Blatt, 1982). Some of the larger fragments have been found at a level lower than their original stratigraphic position, which suggests that the ascent of the mass in the pipe was not powerful enough to support the larger blocks. The blocks subsequently sank against the flow of the rising kimberlite magma.

DIATREME CHARACTERISITCS

Kimberlites can occur as dikes, sills, and diatremes. A diatreme is what is formed by the emplacement of gas-charged magmas when they explode up to the surface. The most common occurrence of kimberlites is that of the diatreme; it is in this form of emplacement that the kimberlite body most often reaches the surface. Kimberlite intrusions are confined almost exclusively to stable cratonic settings, in situations where there was little or no tectonic activity between major crustal plates during the time of intrusion. The typical diatreme intrusion is a conical pipe gently tapering with depth down to a fissure (Hawthorne, 1975), as depicted in figure 1 on the next page. Not all diatremes reach the surface (see figure 2); some apparently did not have the volatile energy required for complete penetration to the surface. In situations such as this, the kimberlite body is referred to as a "blow", which is a blind diatreme

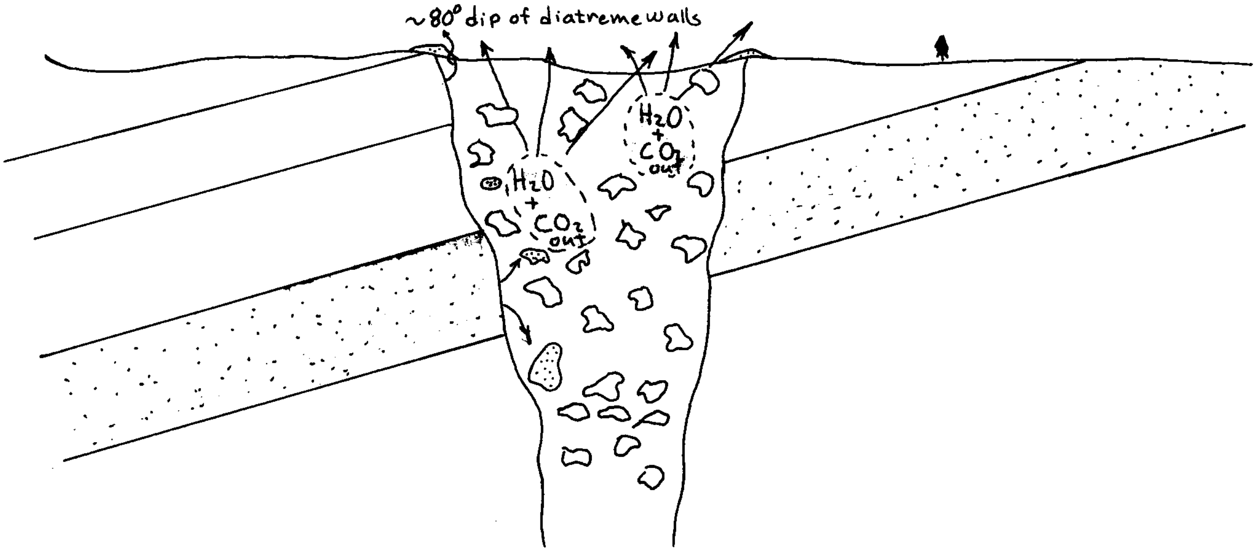


Fig. 1 **A DIATREME** - breaching the surface violently expels large amounts of it's volatiles. Large block of sandstone slides down the pipe due to its size. A low cone of ejected material may be present.

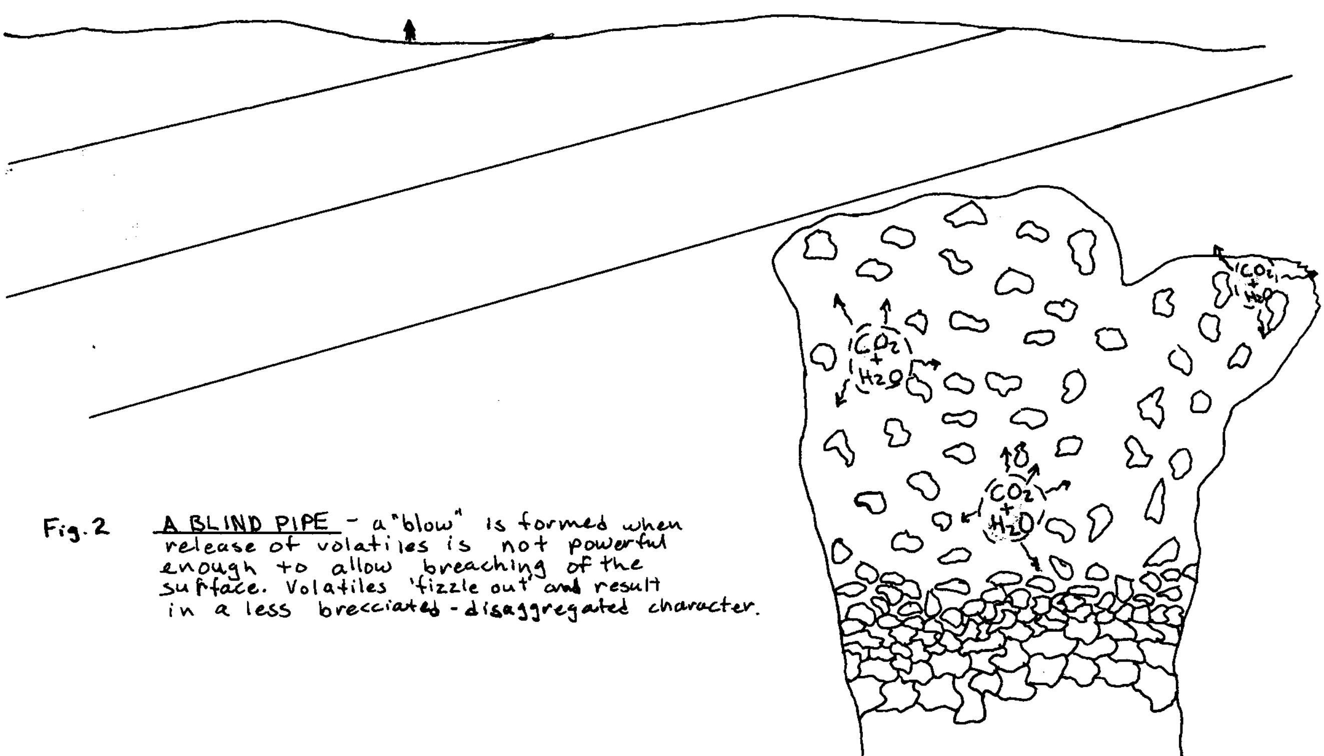


Fig. 2 **A BLIND PIPE** - a "blow" is formed when release of volatiles is not powerful enough to allow breaching of the surface. Volatiles 'fizzle out' and result in a less brecciated - disaggregated character.

dead-ending below the surface.

If the kimberlite body does penetrate to the surface, a low cone of ejecta may accumulate around a shallow crater in the center. The crater can be on the order of a few meters to several hundreds of meters wide, and as soon as the crater is formed erosive processes will begin to redeposit the ejecta wihtin the crater as roughly laminated clastic lacustrine deposits. The grain size of the redeposited ejecta ranges from coarse near the margin to fine near the center of the crater.

Different types of kimberlite can be produced from separate phases of a single intrusion. Textural characteristics are determined by the force with which each intrusive phase is made. Gentle upward stoping in a magmatic body will yield a porphyritic texture, and allow wallrock xenoliths to remain essentially intact. More violent episodes of intrusion thrust the mass of kimberlite and the xenogenic material upward in a dissarray of gas-solid fluidized flow. Intergranular boundaries of crystals contained in a brecciated kimberlite will be sheared and broken, and xenoliths of clastic sedimentary origin may be highly disaggregated and unevenly distributed within the other material. Eddy and swirl flow patterns are visible in some bodies of brecciated kimberlite which attests to the violent, fluidized nature of this mode of intrusion. (Hawthorne et al., 1979).

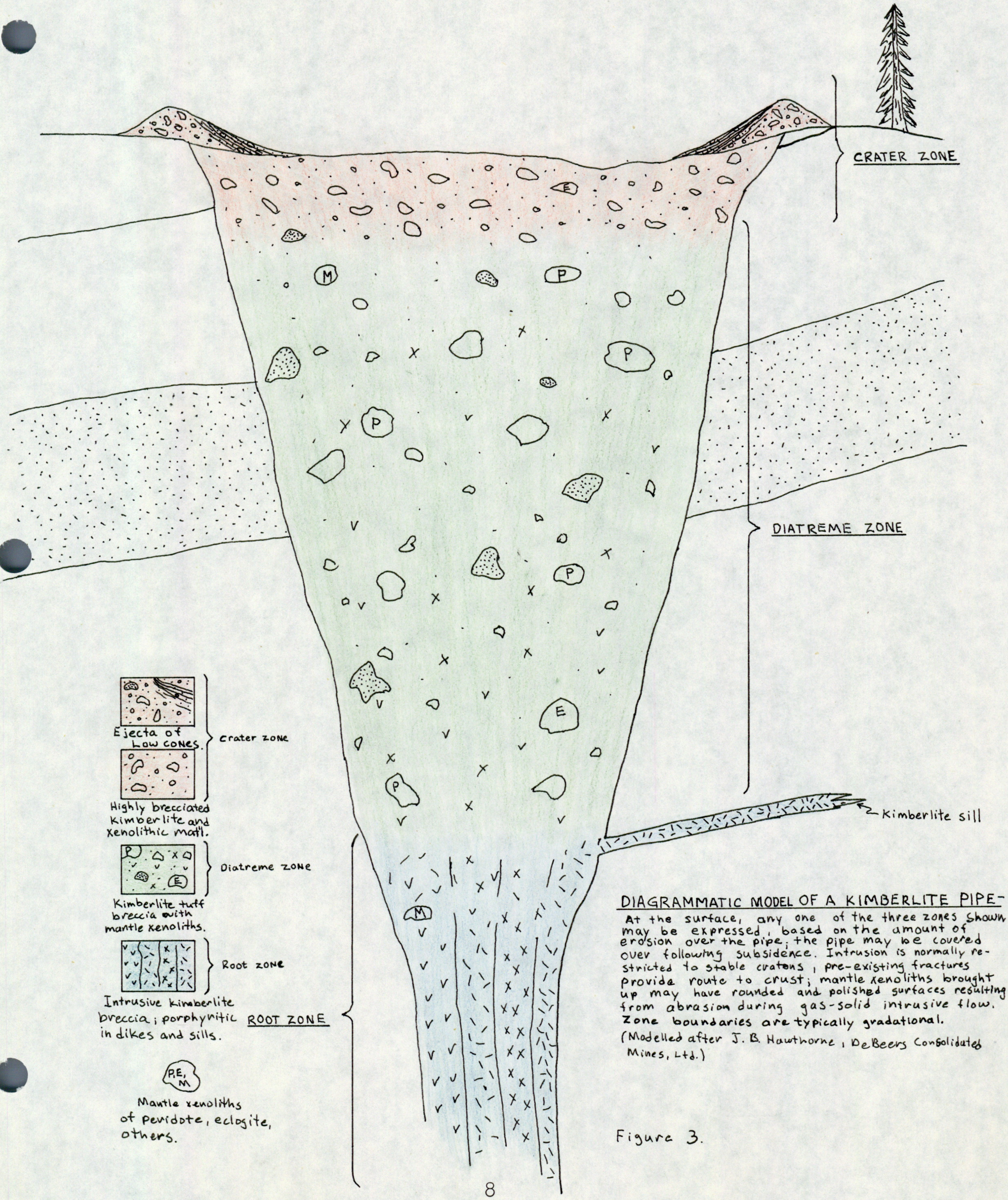
Both explosive and gentle "seeping" phases of kimberlite intrusion have been identified in the field, and in many cases both can be observed in one pipe. The Dokolwayo pipe in Swaziland is a pipe exhibiting both explosive and intrusive phases (Hawthorne et al., 1979). Multiple episodes of intrusion at Dolkowayo have produced widely different textural affinities, the younger phases coring the older.

DEPTH ZONATION

The surface expression of a kimberlite pipe, the textural characteristics, and the overall shape of the body will mostly be a function of the level to which the pipe has been eroded. Clement (1979) has defined three vertical zones within a kimberlite diatreme (see figure 3).

The deepest zone, the root zone, is characterized by a fresh, porphyritic texture, which definitely reveals the igneous nature of kimberlites. In this zone, euhedral crystals of olivine, phlogopite, and spinels are seen, together with phenocryst and matrix associations, and thermally altered included material. Intrusions in the root zone generally exhibit dike-shaped cross sections. The intrusions penetrate into pre-existing fractures deep within the lower crust. The walls of the dikes are highly irregular and nearly vertical. A great deal of erosion has to have occurred to reveal these characteristics of kimberlite intrusions. Hawthorne (1975) has identified distinct and separate necks making up the root zone of bodies in the Kimberley district, South Africa. The root zone rocks consist of different types of kimberlite intrusive breccias.

The intermediate zone, the diatreme zone, is characterized by its high content of mantle and crustal xenoliths,



DIAGRAMMATIC MODEL OF A KIMBERLITE PIPE-
At the surface, any one of the three zones shown may be expressed, based on the amount of erosion over the pipe; the pipe may be covered over following subsidence. Intrusion is normally restricted to stable cratons, pre-existing fractures provide route to crust; mantle xenoliths brought up may have rounded and polished surfaces resulting from abrasion during gas-solid intrusive flow. Zone boundaries are typically gradational.
(Modelled after J. B. Hawthorne, DeBeers Consolidated Mines, Ltd.)

Figure 3.

embedded within a kimberlitic tuff breccia. Rapid release of confing pressure as the kimberlite nears the surface plays a major role in all aspects of the diatreme characteristics in this zone. Xenogenic inclusions show little thermal alteration, and the rock exhibits a less magmatic character overall. The diatreme zone displays steep walls and a more conical cross section than that found in the root zone. The violent release of volatiles and abrasion of confining walls produces an upward expansion in the pipe.

In the uppermost zone, the crater zone, the kimberlite is highly brecciated. This is the site of the most violent phase of the intrusion, and a low cone of ejecta frequently is formed around the margin of the intrusion. Kimberlites that have been only slightly eroded usually will display this low cone. A shallow crater filled with clastic kimberlite and xenogenic material may be present within the marginal cone.

Diamonds and other resistant minerals such as spinels, garnet, and ilmenite are redistributed as placer occurrences by sedimentary processes during the erosion of the crater zone. The discovery of many kimberlite pipes has been based on a recognition of the placer occurrences indicating kimberlite upslope. Detrital diamonds have been found within Pleistocene outwash gravels in norhtern Michigan and Wisconsin, but to date the source has not been pinpointed (Cannon and Mudrey, 1981). The diamonds were transported in a southeast direction by Pleistocene glaciers. Several cryptovolcanic structures have been identified northeast of where the diamonds were found, and one or more of them could be kimberlite pipes. Although some of the structures are covered by collapsed younger strata, they show promise of being kimberlite pipes. High positive magnetic anomolies exist over the structures. If these structures are kimberlite pipes, and they were the source of the outwash diamonds, then the crater zones likely were eroded before they were covered by the younger strata.

KIMBERLITE MAGMA GENESIS

Several reasonable explanations exist for the origin of kimberlite melts in the mantle. Partial melting of peridotite in the presence of high concentrations of CO_2 and H_2O, and an origin through fractional crystallization are two of the most highly supported genetic models.

Partial melting of mantle peridotite

In this model, peridotite partially melts in the absence of vapor; meaning the volatiles CO_2 and H_2O are stored in the liquid phases of phlogopite and carbonate minerals. The embryonic stages of melt genesis are believed to occur in the upper mantle at depths greater than 150 kilometers. At this depth, pressures exceed 35 kb., and dolomite formation in the presence of even slight amounts of CO_2 is easily achieved within a peridotite melt (Wyllie, 1979).

Dolomite, and phlogopite, amphibole and magnesite effectively buffer the vapor phase in the peridotite, and aid in the formation of low silica melts, making kimberlite genesis possible. Eggler and Wendlandt (1979) reported kimberlitic magmas formed from the partial melting of a peridotite containing CO_2 and H_2O at pressures between

50 and 60 kb. High CO_2 and H_2O concentrations severely depress the melting point of peridotite when they are present in the upper mantle. By using synthetic kimberlite comparable to those of the Lesotho region of South Africa, and by using the Lesotho geotherm, Eggler and Wendlandt (1979) calculated solidus and liquidus curves that indicate a depth of generation near 170 km. at a pressure of approximately 53 kb., and a temperature near 1160°C. It is clear that kimberlite melts are generated at great depths and hence great pressure, and that if CO_2 and H_2O from vapor phases in a mantle peridotite are buffering the melt, then melting must occur. Kimberlite and perhaps other alkalic melts are produced, and they subsequently are intruded into the lithosphere beneath the continental crust (see figure 4).

Fractional Crystallization

Fractional cystallization of mantle picrite is also supported by several researchers as a source for kimberlite melts. The findings of Gupta and Yagi (1979) suggest that separation of an eclogite fraction from a nepheline-normative picrite will yield a liquid low in silica, calcium, and sodium, but enrichedin magnesium, titanium, and iron oxides. This is about the composition of a typical South African kimberlite, and if volatiles are present in the melt, kimberlite could evolve from the parental picrite melt (see figure 5).

Those researchers opposed to the fractional crystallization model suggest that basalt must be closely associated with any alkalic melt produced, because picrite is essentially an olivine-rich basalt to begin with. Since the

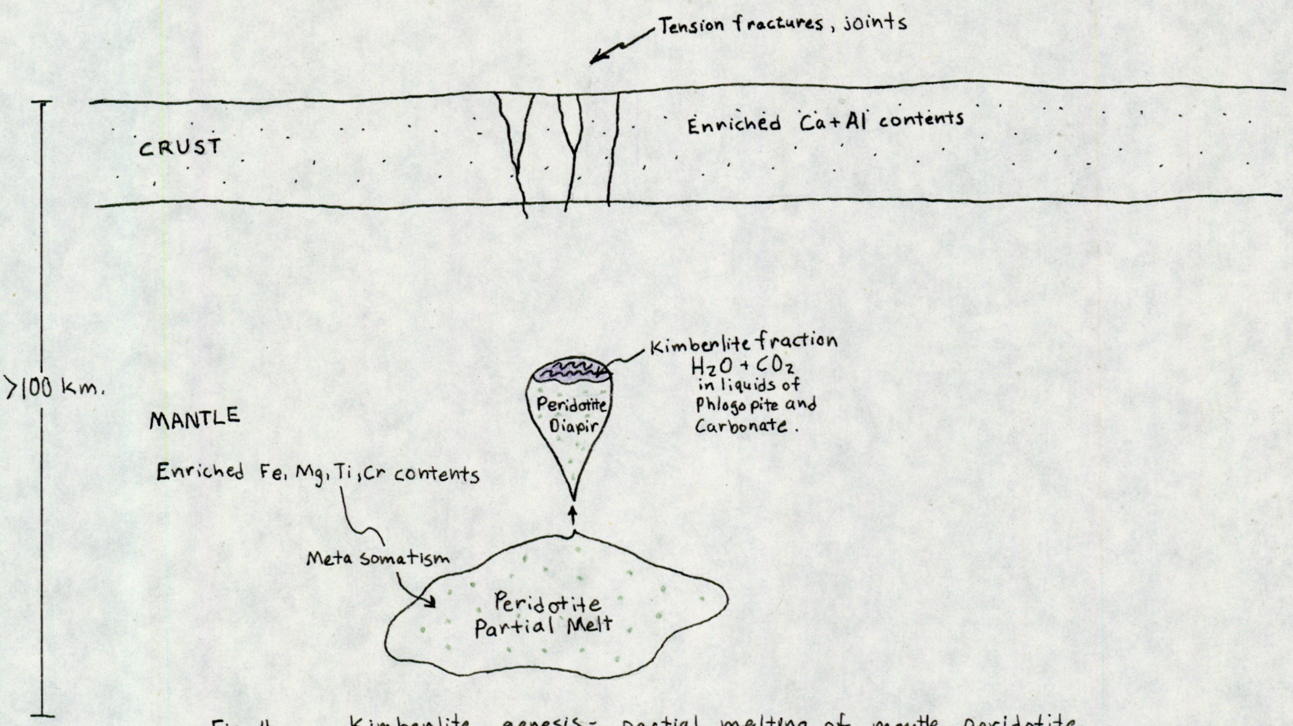


Fig. 4 Kimberlite genesis- partial melting of mantle peridotite by convective heating or pressure drop; Diapiric transport of magma to surface through deep tension fractures and joints. (Modelled after Green and Gueguen)

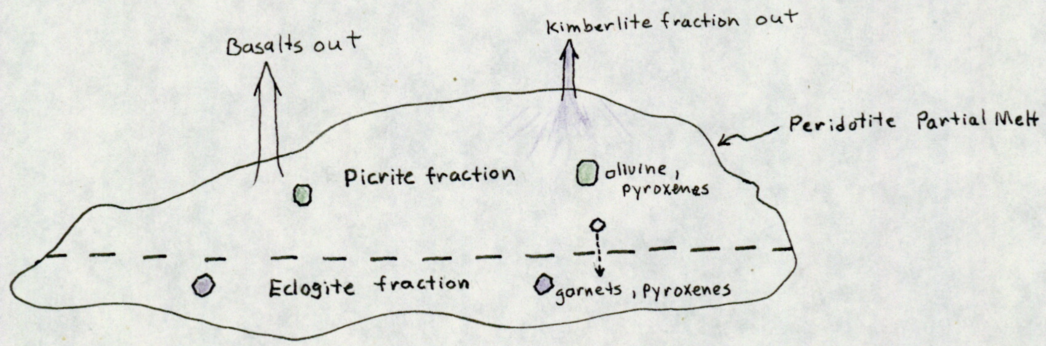


Fig. 5 Fractional crystallization- leading to kimberlite evolution and separation; Basat eruption depleting melt of Ca + Al. Formation of kimberlite in this model calls for substantial amounts of Fe, Mg and Ti to be present; enrichment in Ca + Al on ascention (in equilibrium with wallrock).

alkalic fractions are smaller in relative percentile concentration than are the basic fractions in most picrites, the alkalic melts produced would have to originate from huge picrite melts, or from several small-scale melts of picrite. Hence a kimberlite in this system would have to compete with a basaltic liquid for iron, magnesium, titanium, etc., making kimberlite separation difficult.

Melt Compositions

Basalt eruptions as volumnuous as those recorded at the Earths' surface can deplete a mantle peridotite melt in calcium and aluminum; this is possible because basalt is a primary product of melted peridotite. However, kimberlites are enriched in calcium and aluminum making it necessary for enrichment in these elements to take place somehow prior to kimberlite emplacement in the crust. Crustal contamination seems to be a viable mechanism for enrichment in calcium and aluminum, but this might also yield large amounts of silica, which is not a characteristic of kimberlites. In light of this, absorption of calcium and aluminum still seems to be the most probable method of enrichment.

Boettcher, et al. (1979) have suggested that the high concentrations of titanium, potassium and iron present in kimberlites may be related to enrichment by mantle metasomatism. Enrichment is achieved in mantle metasomatism by the replacement of minerals low in concentration of titanium, potassium, and iron by minerals rich in these elements; the reactions are set up by the invasion of fluids rich in the aforementioned elements from sources external to the parental melt. Introduction of fluids rich in these elements could yield megacrysts of phlogopite and amphiboles, which also carry high values of water and aluminum. Spinels and perovskite also would account for some of the high titanium concentrations found in many kimberlites.

Further enrichment in calcium, aluminum and titanium may be attributed to the throttled ascention of the kimberlite body, during which time the intrusion might attain an equilibrium with surrounding wallrock of the lower to middle continental crust.

Anomolous high concentrations of the light rare earth elements (LREE) and of thorium were found in Riley County, Kansas kimberlites by Cullers et al. (1982). An origin by crustal cantamination is not acceptable here because of the presence of only small amounts of SiO_2, Al_2O_3, and Na_2O found in these rocks. All of these compounds normally are quite abundant in the crust. Fractional crystallli-zation is not an acceptable alternative because garnet and clinopyroxene (diopside) that would be removed from the kimberlite melt would lower the concentrations of compatible elements such as cobalt, chromium, and scandium. However, these elements are highly concentrated in kimberlites.

Melting of mantle peridotite, rich in garnet fractions, in the presence of the LREE and of thorium is suggested to have produced the Riley County kimberlites. The LREE and thorium could have been introduced by mantle metasomatism (Boettcher et al., 1979) or they could have been present in the peridotite prior to partial melting. Transport of the elements within the kimberlite intrusion body appears to have been accomplished by the volatile phases within the body (Cullers et al., 1982). Large amounts of CO_2 and H_2O at mantle pressures can selectively carry LREE and thorium and transport them to levels where lower pressures convert them back to their mineral phases. Crystallization permanently fixes the elements within mineral phases.

Kimberlite Ascention

A melt produced in the mantle somehow would have to ascend from the asthenosphere to the lithosphere in order for it to intrude the crust. Formation and injection into the asthenosphere of a peridotite diapir at depths below 160 km., at pressures between 50 and 60 kb. and temperatures around 1300°C, would partially melt the peridotite, yielding a kimberlitic liquid. As the diapir begins begins to rise, as the result of overlying pressure and density differences between the diapiritic mass and the rock in the asthenosphere, the kimberlite fraction would concentrate within a portion of the structure. Upon reaching the lithosphere the kimberlite may contact a pre-existing deep-seated fracture, freeing it from the diapir. At this point explosive intrusion of the kimberlite magma would be initiated.

Partial melting of a peridotite diapir to yield a kimberlite melt may be a common event, given the temperatures and pressures of the upper mantle (Eggler and Wendlandt, 1979). However, kimberlites are rare occurrences in the continental crust, because an appropriate tectonic setting for emplacement is not easily found. Tension fractures and/or deep high-angle faults extending to the base of the lithosphere are found in a number of localities, but for kimberlite pipes to occur the kimberlite melts must form directly below these structures.

Kimberlites have never been found in the oceanic crust nor is it thought that they will be found there. The level to which a diapir can rise in the asthenosphere is higher below the oceanic crust, because the oceanic crust is much thinner than the continental crust. At the higher levels, liquids of basaltic composition are likely to form from a peridotite diapir melt rather than kimberlitic liquids, due to the conditions of temperature and pressure within the asthenosphere below the oceanic crust. Indeed the ocean basins are primarily basalt, and kimberlitic magma rising to this level presumably would be converted to basalt upon reaching the surface.

PROSPECTING FOR KIMBERLITE

The use of several methods have been employed in the search for kimberlite. The practical applications of each are limited by the conditions of topography, ground cover, drainage, and various other factors. Similarities exist in almost all kimberlite districts. Detailed studies in any area should be preceded by an evaluation of geologic maps, areal photographs, and evidences provided by previous prospecting operations. A systematic approach to exploration consisting of three steps is recomended by Hausel et al., (1979) in the search for kimberlite intrusions. First, prospecting should be conducted including sampling and mapping operations in the target area. Secondly, geophysical and ground surveys should be conducted (delineation techniques according to Hausel et al., 1979). Assessment is the third step in exploration, and it is done to determine whether or not minerals can be extracted at a profit from an identified site.

Prospecting may first be initiated by the examination of areal photographs and images produced by remote sensing. These methods have been utilized to a large extent in the last couple decades as they have become more accessible to prospectors all over. These methods outline target areas for later exploration because structural trends and zones of crustal weakness can easily be identified from the images, and these features are of use in planning ground surveys. The images also can be consulted when more information is needed at later stages in exploration.

Remote sensing imagery sometimes will reveal variations in vegitation, often expressed as semi-circular patterns, indicating different types of plants growing in the soil over diatremes. For example, false color imagery may depict lush grasses growing in soil over a kimberlite pipe, because the soil produced from weathering of a kimberlite may be more fertile than that produced over the surrounding country rock. The reverse also may be true, when a clay soil develops from the deep weathering of kimberlite. In this instance, the vegitation may be more lush around the perimeter of the diatreme. Situations such as these are best seen in warm, dry climates where vegetative cover is fairly sparse. Differences in ground cover in areas such as this are more readily apparent than in areas where a large number and variety of plants may be present on the ground. Much depends on the relative soil development over two or more rock types, and care should be taken to investigate these aspects.

Structural evidence can be used to detect kimberlites in some situations. Kimberlite intrusions often occur at the intersection of faults and/or joint sets. Occurrences such as these lend support to the hypothesis that kimberlite intrusions invade deep fractures in the Earths' crust. Identification of structural trends such as described may provide an important key to locating kimberlite intrusions. For example, the lineaments of the kimberlite dikes studied by Hausel et al. (1979) directly mirror the lineaments or systems of joints inherent in the granite country rock of the State-Line District of Wyoming and Colorado. In the Appalachian areas of Kentucky, Tennessee, and Pennsylvania, the intersection of cross-structural lineaments such as tensional fractures and parallel fault systems are the sites of known kimberlite intrusions. Possible new bodies may be found with further detailed study of these Appalachian areas (Parrish et al., 1982).

Alluvial sampling of stream sediments is a reliable means of detecting kimberlite intrusions, because resistent heavy minerals such as chrome-bearing diopside, pyrope garnet and magnesian ilmenite may be eroded from a kimberlite body and carried downslope by mass wasting and alluvial processes. Systematic sampling of stream sediments along drainages normally is the first phase of heavy mineral exploration, and once indicator minerals are found additional more intense sampling is conducted to pinpoint the source. Large target areas can be representatively sampled by spacing the samples no more than one mile apart (Hausel et al., 1979); follow-up sampling in areas shown to be of interest would be on a smaller scale, perhaps with samples spaced every 500 feet or so.

Eluvial evidence of kimberlite can be observed by recognition of the distinct assemblage of alteration minerals produced during surface weathering of kimberlite. This set of alteration minerals includes montmorillonite, chlorite, serpentine, talc, and calcite. Presence of these minerals gives the ground over a weathering kimberlite body a blue-gray color, called "blue ground" by the diamond miners. In addition, nodules of lower crustal and mantle material frequently are found over exposed kimberlite intrusions. Mantle nodules of eclogite, peridotite, carbonatite, and picrite have been used to locate kimberlites, by finding them over and downslope from exposed intrusions (Hausel et al., 1979). Macrocrysts of pyrope garnet and magnesian ilmenite, as well as crystals of chrome diopside, derived from xenoliths can be found scattered around eluvial deposits. All of these are very useful indicators of the presence of kimberlite.

If the prospecting techniques mentioned above are effective, there may be no need for additional methods of exploration. However, less tedious techniques often can lead to the discovery of kimberlite pipes.

Deliniation methods such as electrical resistivity surveys, and magnetic and seismic surveys can be used to locate specific structures suspected of being kimberlite pipes. The results can also be misleading. Magnetic anomolies may be related to ultramafic boulders in a boulder train remnant of glacier ice flow, and almost any counductive body can produce an electric anomomly. Hence, all possible sources of information should be consulted prior to employing the geophysical methods.

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